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Coherent Structure

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Our mental picture of turbulence structure has progressed from the hypothesis that it mimics molecular motion to the belief that turbulence is highly organized though there is some question as to whether there has been an overshoot, i.e., an over-selling of coherent structures in general on the strength of experiences in mixing layers. A brief look at the history is instructive.

- Boussinesq (1883) - "billiard ball" analogy with kinetic theory, leading to the eddy viscosity concept.
- Prandtl (1925) -mixing length "lumps" (apparently inspired by the Ahlborn method of water-surface flow visualization, which forces two-dimensional motion near the surface).
- Theodorsen (1952) - horseshoes of assorted sizes.
- Townsend (1956) - WEAK large eddies with shapes deduced from correlation tails.
- Grant (1958) - STRONG large eddies in boundary layer and wake.
- Bradshaw et al. (1964) - VERY STRONG (but 3D) large eddies in mixing layer.
- Crow &Champagne (1971) - VERY STRONG 2D (but Re-dependent?) orderly structure in mixing layer.
- Brown & Roshko (1971) - confirmed Crow & Champagne picture, with the implication that the 2D vortex roll structure may not be very Re-dependent.

Between 1964 and 1971 Townsend's large eddies grew into orderly structures! Unless the latter term is used to distinguish unusually strong, or unusually long- lived, or unusually two-dimensional large eddies from the norm, it is perhaps a confusing change from Townsend's more descriptive label, at least for discussion of the dominant eddies away from the inner layer of a wall flow. Certainly, the main impression one gets from the last 15 years' research is that large eddies / orderly structures *are* longer-lived than was previously thought - and of course that in the mixing layer the orderly structures are essentially two-dimensional unlike the traditional picture of turbulence. Now the time scale (turbulent kinetic energy)/(dissipation rate) or TKE/(production rate) is always a representative of the energy-containing, shear-stress-carrying eddies. Thus an unusually long eddy lifetime (as deduced from flow visualization, say) implies an unusually small rate of energy transfer (small dissipation rate) in that part of the turbulence - that is, an unusually weak coupling between the long-lived eddy and the rest. This suggests that a two- dimensional eddy may be exceptionally long- lived, simply because it does not share so directly in the vortex- stretching "cascadse" of energy as three- dimensional eddies do. The mixing-layer simulations of Metcalfe et al. (1987) make it clear that a mixing layer with disturbed initial conditions can have a large-eddy structure consisting of long but finite vortex rolls swept back at various angles, presumably strongly interacting with each other and therefore having shorter lives than the parallel two- dimensional rolls observed by Brown & Roshko and others. We need to make sure we are chasing the right, representative eddies! A related point is that our main object in studying any turbulent flow is to improve predictions of shear stress, and we should therefore be studying the eddies that carry, or influence, the shear stress. It seems a good general principle that presentations of educed eddy shapes should be accompanied by an estimate of the fraction of total shear stress that is carried by eddies of that shape.

According to Townsend's large eddy equilibrium hypothesis, turbulent mixing (i.e., shear stress) was supposed to be controlled by large eddies (more or less filling the shear layer but not carrying much of the turbulent energy). This is a paradox - how can eddies be weak in energy, strong in shear stress? "Weakness" of the large eddies was required for the "equilibrium" hypothesis. The result was an eddy viscosity for the smaller, energy-containing eddies. Grant (1958) showed that large eddies in boundary layers and wakes did contain a large fraction of the turbulent energy. This killed the equilibrium hypothesis - but the concept of large eddies as large contributors to mixing should not have been largely ignored for the next 15 years.

The main questions about "orderly structures" or "large eddies" are:

(i) How different are they in different shear layers?

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(ii) Can we usefully combine a model of the orderly structure with a cruder representation of the small-scale, less-well-ordered eddies as in Townsend's large- eddy equilibrium hypothesis or the Murthy & Hong Large Eddy Interaction Model?

(iii) What about the all-important boundary layer? (Especially the outer layer - engineers ***think*** they know all they want to about the inner layer.)

Suggested **answers**: -

(i) Large "orderly structure" is just an extreme case of Townsend's large eddies, which were always envisaged as different in different flows. Therefore study of orderly structure is not a route to a universal model (at least at Reynolds-averaged level). The persistence of orderly structure is critical to the success of "zonal average" modeling - if large eddies/orderly structure persist for a long time after a change of zone, the change of empirical coefficients at the edge of a zone will have to be governed by a complicated rate equation.

(ii) Except in the mixing layer and the inner layer of a wall flow, the background turbulence carries a very significant part of $\overline{uv}$ - but maybe we can manage with just a few modes (not necessarily superposable Fourier modes).

(iii) In the outer part of a boundary layer, the large eddies/structures seem to be not-very-well-ordered eruptions, probably horseshoe- or hairpin-like (beware low- Reynolds-number simulations), because the outer structure depends on viscosity up to $Re_\theta = 5000$ (as shown by wake parameter behaviour - see also Murlis et al., *J. Fluid Mech.* **122**, 13, 1982). Since the outer part of the flow presents the biggest challenge to turbulence modeling (provisionally accepting the engineer's view of the inner layer!) study of the more spectacular forms of orderly structure is unlikely to help us with the boundary layer problem. Of course, study of the inner layer is helpful to basic understanding: at least the scaling in the logarithmic region is simpler than usual even if the turbulence is not.

As a final comment, it is still difficult to see how conditionally-sampled data on orderly structures, whether from simulations or from experiments, can actually be used in Reynolds-averaged models, although qualitative understanding is still valuable. However, if we could derive exact transport equations based on some compromise between Reynolds averaging and solution of the time-dependent Navier Stokes equations, we would have a considerably better chance of using our knowledge of orderly structures.